Mid-InfraRed Optimized Resolution Spacecraft (MIRORS)

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ABSTRACT

A concept study was performed in 199-$ to develop a mission design for a telescope to achieve the highest possible spatial resolution in the 10-30 micron range within a $'200 million mission cost cap. The selected approach for the resulting Mid-InfraRed Optimized Resolution Spacecraft (MIRORS) concept design utilizes a partially filled five meter aperture. A simple deployment scheme permits this spacecraft to be fit within the volume envelope and mass capabilities of a Med-Lite launch vehicle. Low bandwidth cryogenic actuators, which dissipate no heat once set, will align the optics after on-orbit thermal stability is achieved. Image stabilization, tine pointing and stray-light control arc achieved through use of a novel actuated Offner relay. Image reconstruction techniques developed for IRAS will be used to deconvolve nearly diffraction-limited images at 10 microns (FWHM -0,5 arcsec).

A Lissajous orbit about the L_2 sun-earth libration point (sun-earth-L_2 on a straight line) is adopted because its extremely stable thermal environment results in correspondingly high telescope mechanical stability and optical performance, This orbit, combined with a spacecraft configuration which incorporates an inflatable sunshield and a deployable four-stage v-groove thermal shield, enables the optics to radiatively cool <25 K. The large format focal plane will be actively cooled to <8 K by a Vibration-free, long-life sorption refrigerator.

Keywords: infrared telescope, partially filled aperture, image reconstruction, infrared astronomy, passively cooled telescope

1. MISSION CONCEPT OVERVIEW

The InfraRed Astronomical Satellite (IRAS) revolutionized our view of the infrared universe with its all-sky survey in 1983. The current and planned observatory-style infrared missions, 1S0 (1 995) and SIRTF (-2002), will achieve impressive sensitivities with mirror diameters of 0.6 and 0.8m respectively. We concern ourselves with the next generation of infrared telescopes, and tackle the problem of how to improve spatial resolution in an era of tight cost constraints.

The Mid-InfraRed Optimized Resolution Spacecraft (MIRORS) design, first set forth in December 1994 to the NASA New Missions Concepts Program, uses several novel elements to achieve high spatial resolution with a low-cost, long-lived infrared space mission, The basic idea is a 5 m telescope with a partially filled aperture, made up of four mirror segments arranged in a tee configuration, to provide high spatial resolution while minimizing launch mass. Proven image reconstruction techniques provide diffraction limited sub-arcsecond images akin to those from a 5m class filled aperture. To fit within the Med-Lite launch shroud, three of the four mirror segments arc mounted on deployable trusses.

Building on the radiatively cooled telescope ideas advanced by Hawarden and colleagues,' the thermal design incorporates cryocoolers and inflatable thermal shields to eliminate the normally required cryogen dewar, increase mission lifetime, and to further reduce mass and volume. Low bandwidth cryogenic actuators, which dissipate no heat once set, will focus and align the optics after on-orbit thermal stability is achieved. The proposed Lissajous L_2 orbit (sun-earth-b) provides the optimum orbit to achieve high mechanical and thermal stability, which in turn provides a stable point spread function (['SF), The spacecraft in this orbit is oriented such that it is always facing the sun and earth. The telescope optical axis is oriented perpendicular to the spacecraft axis. By rotating the spacecraft on its axis, the telescope is able to view a 360 degree band passing through the ecliptic poles, which is 15 degrees wide, at any time. The telescope will therefore have the ability to image any point in the full sky in 6 month intervals.

An existing, commercially available (TRW) spacecraft bus is capable of achieving all power, structural, telemetry and coarse guidance requirements for the spacecraft. To achieve sub-arcsecond stable pointing, a tip-lilt mirror in a simple Offner relay is used to stabilize the infrared image on the focal plane. in addition, the Offner relay provides an opportunity to implement cost-effective sway-light control, Recently flight-qualified workstation class computers will be employed to minimize mission operations expenses through on-board processing and semi-autonomous operation. A moderate sized launch vehicle, such as the Med-Lite, can achieve the proposed L_2 orbit with adequate margin at the estimated MIRORS system weight of 565 kg, The MIRORS spacecraft is shown in Figure 1.

Since the original MI RORS concept was conceived, several other proposed spacecraft (PSI, FIRE) have adopted and further developed the L_2 orbit, spacecraft configuration, and thermal design described in this paper, In addition, the integrated design approach embodied in MIRORS was used as the baseline from which the ExNPS mission concepts were developed. Given an anticipated lean funding climate, along with the desire for higher spatial resolution, we anticipate that all infrared space missions after SIRTF will incorporate many elements of the MIRORS design,

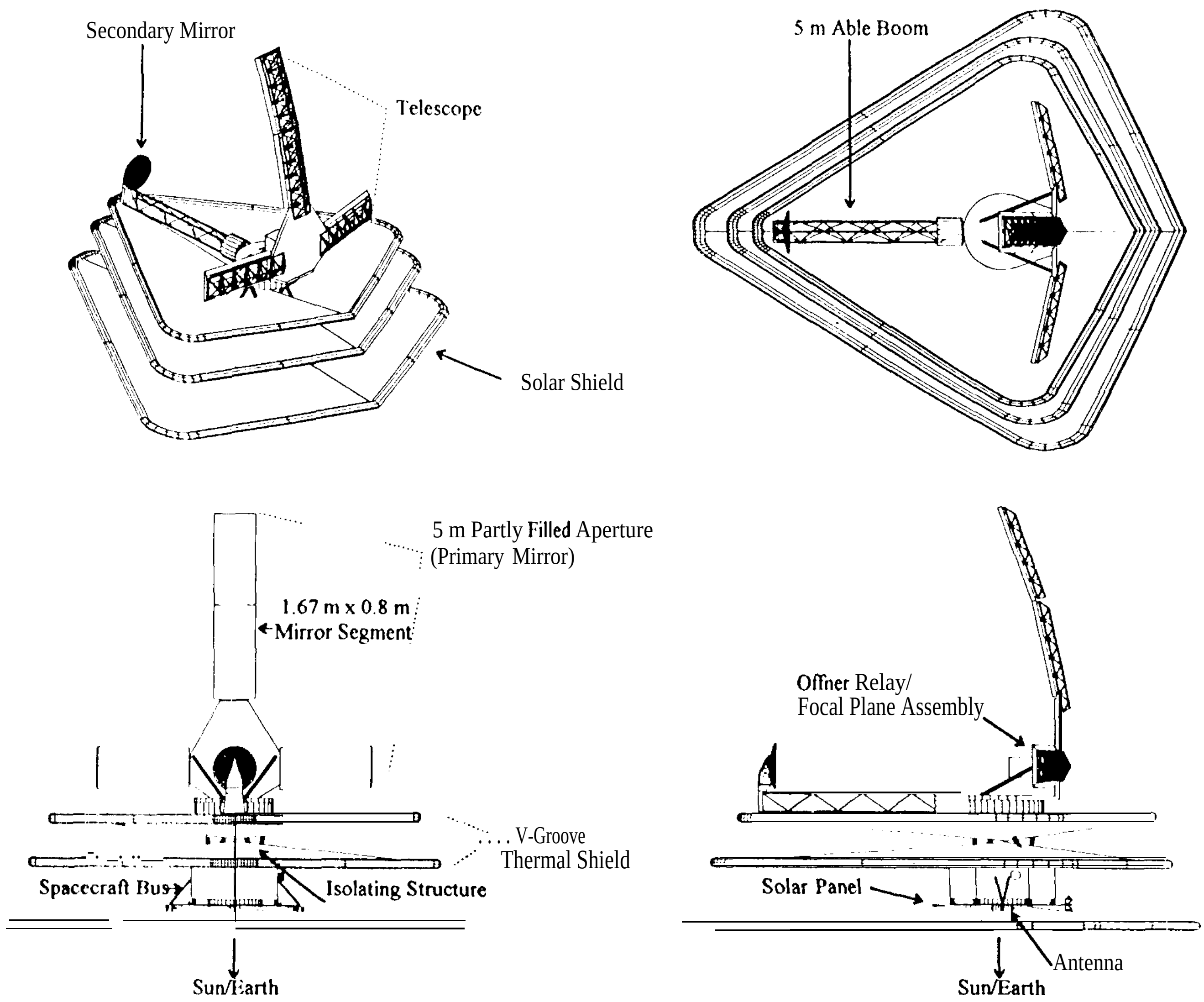

Figure 1, Several views of the MIRORS spacecraft

1.1 The MIRORS telescope

MIRORS is an off-axis f/8.2 conventional Cassegrain telescope (shown in Figure 2). The telescope is nearly diffraction limited at 10 pm, resulting in 0.5 arcsec resolution. The optics prescription has been selected to match 4 detector elements on 50 µm centers to the full diameter 200 µm Airy disk. This enables the PSF to be Nyquist sampled as required for image reconst ruct ion.

The f/1,2 primary is a tee formed by four 1.67 m by 0.8 m fused silica mirror segments arranged as shown in Figure 1. This tee shaped aperture achieves good uv-plane coverage for image reconstruction while minimizing system mass. The segments of this array, as proposed by Eastman Kodak, consist of an ultralight, webbed core (cut from a solid segment using an abrasive water jet) with low temperature fusion-bonded front and back plates. Fabrication of these low mass, high precision mirrors for low temperature operation is within current manufacturing capabilities.

A prime mid-infrared science objective, the detection of debris disks, presents a special challenge due to the high signal ratio between the central star and the surrounding disk, The ability to detect these disks will be strongly affected by the small angle scattering by the optical system. Small angle scattering primarily comes from figure features 1/5 to 1/100 of the

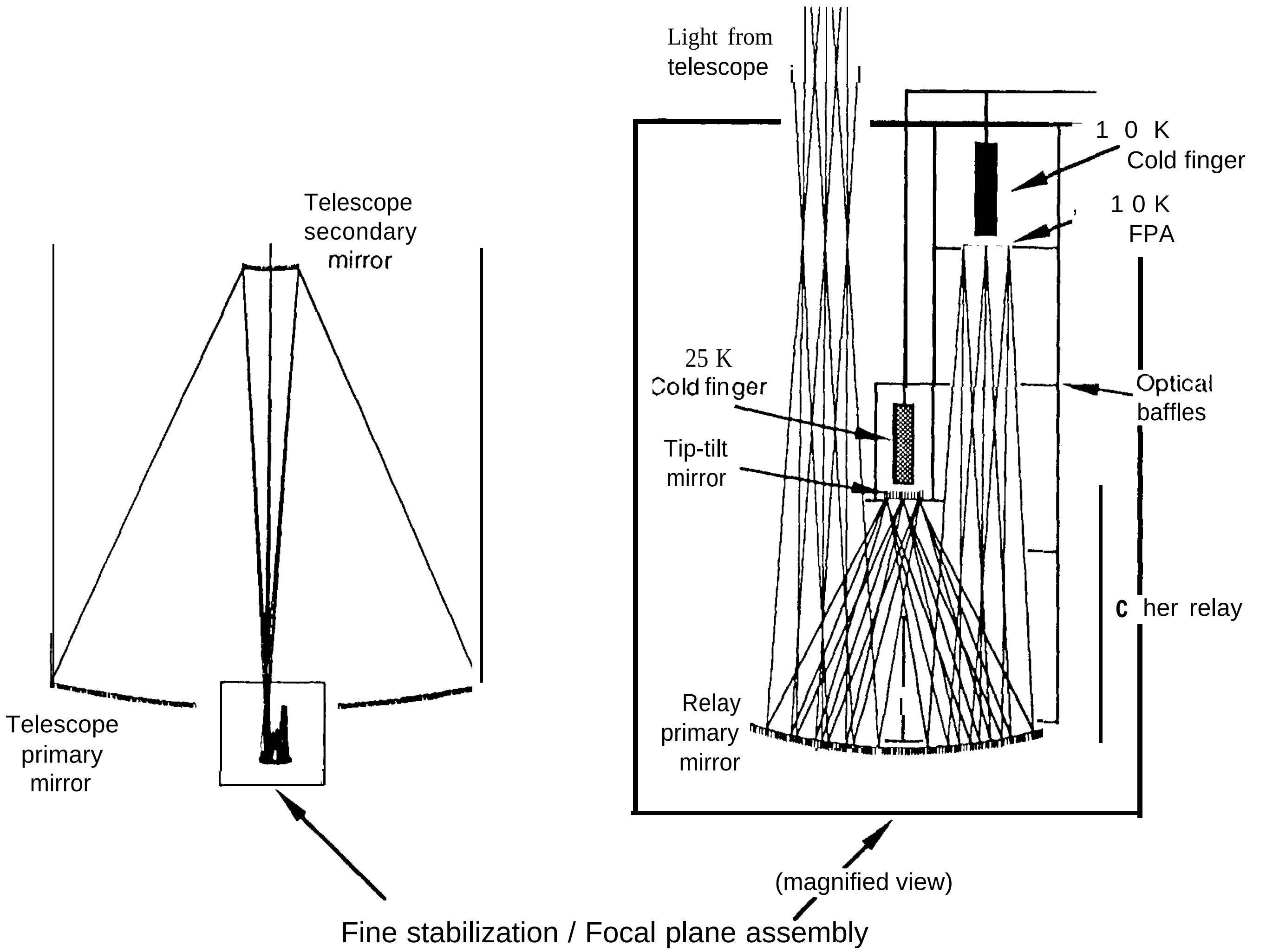

Figure 2. Preliminary design for a 5 meter aperture telescope with image stabilization optics.

aperture diameter. Ion figuring techniques developed at Kodak[2] excel in eliminating this type of figure error. Stray light baffling is readily incorporated into the proposed optical design. Broad angle scattering caused by surface microroughness and segment edge diffraction while of concern, arc of secondary importance in this application.

A key aspect of this mission concept is the usc of an inexpensive, moderate-precision telescope structure. Only the imaging camera, the Offner relay assembly and the inner primary mirror segment on the leg arc fixed in a precision optical assembly. The secondary and the three outer primary mirror segments arc all deployed. The three mirror segments arc mounted on rigid structures which arc hinged at their connections to the fixed central optical assembly. The secondary is supported and deployed by a 5 m Able boom. 'I'o enable the telescope structure to be of relatively low precision, the three deployed mirror segments and the secondary will all have low bandwidth alignment actuators. After launch, orbit insertion, deployment and thermal equilibrium arc achieved, the mirror segments are aligned using these actuators to form a common focus. Manufacturing tolerances, assembly alignment errors, thermal contraction from cooldown, positional shifts from the deployment and misalignment from launch induced stresses are compensated for during this alignment process.

The mechanical design of the telescope will be considerably less expensive and lower mass than a high precision thermally stable design duc to this compliant design approach. Reducing the scope of the engineering effort by at least 50% is central to the development of an affordable large aperture telescope. Substantial cost savings will be achieved through the resulting simplification of the optical alignment process during ground assembly and test, This testing process is very expensive and time consuming for most cryogenic optical systems.

The structure supporting the secondary and the primary optics will be manufactured using low coefficient of thermal expansion material such as titanium or beryllium. 'his structure will be manufactured only to tolerances commonly achieved by numerically controlled machines. The structure supporting the secondary does not interfere with the light paths and therefore dots not affect the system P. SF. Kinematic mounts for the optics have already been developed at JPL for the Precision Segmented Reflector program and by Kodak with the level of precision required for MIRORS. Launch locks will be required for the four mirror segments and the secondary.

A novel magnetostrictive actuator is proposed for telescope alignment. This actuator, based on magnetostrictive materials such as Cryogenic Terfenol-D, works at temperatures between 4 K and 150 K and dissipates no heat once SC(. Actuation is accomplished by mechanically moving a permanent magnet over a Terfenol-D core. In effect this provides a S00 to 1 mechanical reduction of the permanent magnet positional accuracy, thereby enabling very precise alignment to be accomplished. In the configuration proposed it would have a range of 1.25 mm and a resolution of 0.5 pm. Because of the stability of the MIRORS spacecraft configuration in the L_2 environment using our proposed observing strategy, the actuated pri mary's optics do not need a large bandwidth. Actuation is only required for telescope focusing and alignment upon reaching thermal equilibrium. Updates may only be needed monthly instead of every few seconds as is common in ground based systems. Working between 10 and 30 μm considerably relaxes precision requirements compared with visible wavelengths.

1.2 Pointing

Achieving 0.5 arcsec reconstructed image resolution with the MIRORS sensor will require a pointing stability of 0.12 arcsec. 1 'he kcy to achieving this requirement will be to reduce the spacecraft induced image jitter to below O. 1 arcsec. Coarse pointing will bc done by the spacecraft, Fine image stabilization to approximately 0.05 arcsec is accomplished with an actively controlled tip-tilt mirror in an Offner relay located at the focal point near the center of the main optical structure.[3] This actuated Offncr relay is capable of stabilizing an image which wanders radially up to 1 arcmin off the optical axis, while introducing negligible aberrations, This device, shown earlier in Figure 2, consists of two spherical mirrors. The small tip-tilt mirror is actuated by low bandwidth magnetostrictive actuators and is actively cooled to 25 K by the first stage of a sorption refrigerator, The size of the required mirror is small enough that no reaction mass is required,

Data for driving the tip-tilt mirror will bc provided by on-board processing of a star mapper's visible light CCD image, Subpixel movement resolution, of Nyquist sampled images, is readily achieved by doing centroid location. This approach ensures that there is considerable margin in the pointing knowledge for accurate optical actuation. Absolute pointing knowledge can also be gained in a similar method through comparison of CCD visible light centroid locations with the available star catalogs. Wc expect that inexpensive star mappers using this approach will be available in the near future based on recent advances in CCD and CPU technologies.

A significant advantage of this actuated Offner relay is the relative case with which stray-light control can be implemented. The relay provides a real, demagnified image of the entrance pupil near the relay secondary. A physical stop placed near the demagnified pupil image and baffles in the relay assembly allows cost-effective stray-light control to be accomplished.

1.3 Focal plane assembly

The proposed instrument design is for an imaging camera incorporating a large format Si:As BIB detector array. Si:As BIB detectors arc now being fabricated in 256^2 arrays and have the potential to be produced in much larger sizes (a 1024^2 array was assumed to be available resulting in a 128 arcsecond fleld-of-view), These detectors are now routinely flat to one percent in responsivity and uniformity and have reasonable quantum efficiency between 5 and 30 microns, It is currently projected that cooling the Si:As BIB focal plane assembly (FPA) to 8 K using a hydrogen sorption refrigerator will allow minimum dark current levels to be achieved. If this development is not realized, the FPA will be cooled to 4 K via an additional helium/charcoal sorption refrigeration stage.

1.4 Image reconstruction

The partially filled aperture (PFA) mirror is also known as a Fizeau style interferometer. The mirror segments comprise part of a larger parabolic surface so that light rays arc brought to a common optical focus, as happens in a conventional reflecting telescope. There is little reason to build such telescopes on the ground, at infrared or shorter wavelengths, as the earth's atmosphere is either opaque (UV,IR) or its distortions preclude diffraction limited seeing (optical). However the large cost savings of launching low-mass mirrors is a persuasive argument for using partially tilled aperture mirrors in space.

The utility of partially filled aperture mirrors in space depends on the quality of the image reconstruction and the stability of the PSF. While the raw image provided by the tee shaped aperture is fairly good, image processing will still be required. The basic imaging concept is analogous to the process of cleaning dirty maps in interferometry to produce a well behaved image. The reconstruction preserves clearly real features in the data, reduces the sidelobes and thereby converts the image into a form much easier to interpret. The completeness of the uv-plane coverage provided by the tee shape aperture makes image processing relatively simple for MIRORS compared with other PFA concepts.

There area number of image reconstruction techniques available. Data from the IRAS satellite, which is very analogous that generated by the tee apert ure, gives an excellent illustration of the power of image reconstruction. HiRes processing, in long usc at IPAC, implements the Maximum Correlation Method (MCM), a variant of the Richardson-Lucy technique optimized for IRAS data.[4,5] The results of HiRes processing on IRAS data arc illustrated in Figure 3, which shows the galaxy M101 at 60 microns, before and after image reconstruction. There is an enormous increase in detail after reconstruction. Both diffuse galactic emission and prominent star forming regions arc visible. The 1 arcminute resolution of the reconstructed image is nearly diffraction limited. To illustrate the power of MIRORS we note that a MIRORS image of nearby galaxies like M101 will show the same clarity and detail as an optical image, but without the obscuring effects of dust extinction so prominent at optical wavelengths.

1.5 Orbit and telescope thermal control

An important component of the mission is a 90,000 km radius Lissajous orbit about the collinear sun/earth libration point L_2 at 1.5 million km from the earth. The thermal and environmental stability of this location greatly simplifies the mission design compared to previously considered large aperture systems, Orbit insertion can be achieved through usc of a lunar swingby without any extra Av beyond that required to reach the moon, The swingby targeting determines the final amplitudes of the Lissajous L_2 orbit. Maintenance of this orbit requires xy control of 4 ntiscc/year with corrections made every 6 to 8 weeks. Z-axis control requires 25 m/s/year Av with corrections made every 3 months.

Systcrn mass can be substantially reduced and system life substantially incrcased by synergistically combining a good thermal environment (orbit), using radiators at as low a temperature as possible for thermal and optical shielding and employing newly developed active coolers for thermal control of the focal plane assembly, In this Lissajous L_2 orbit, the earth and sun arc always on the same side of the spacecraft and separated by only 3,4 degrees. The moon and sun are

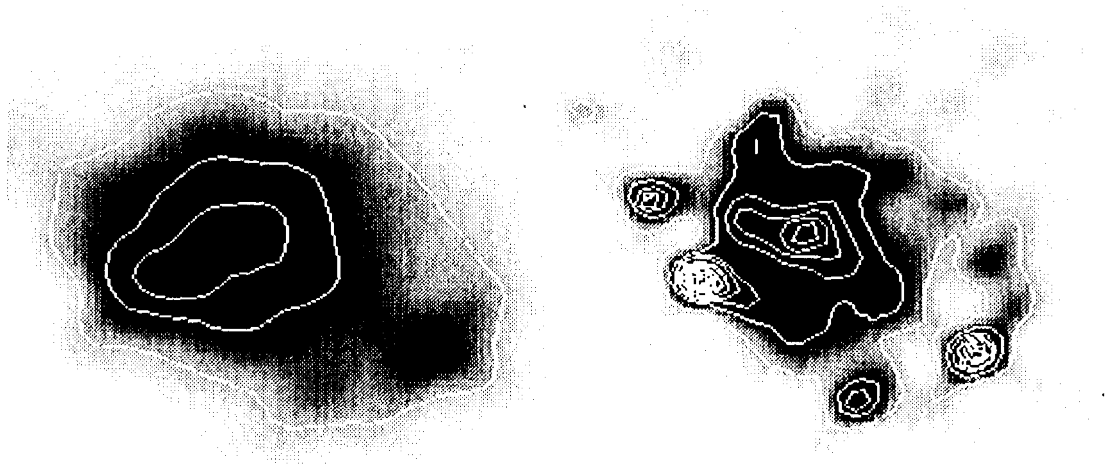

Figure 3. M101 at 60 microns as seen by IRAS, before (left) and after (right) image reconstruction. Notice the spiral arm as delineated by a string of HII regions, emanating from the north, arcing west then south. Bright compact sources correspond with known HII regions, and also appear at other IRAS wavelengths. Field 20 arcminutes on a side. The resolution improves by a factor of 5 after image processing and approaches diffraction limited performance.

separated by a maximum of 17.4 degrees. This orbit enables a spacecraft configuration placing all of the warm structure (spacecraft bus, communicant ions antenna, solar cells, and solar shield) on the same side (see Figure 1). A deployable v-groove thermal shield, or radiator, in combination with G-10 composite struts is used to thermally isolate the telescope thereby allowing it to radiatively cool to cryogenic temperature. Thermal models of this Combination of a solar shield with a four-stage v-groove radiator predicted a temperature of <50 K on the telescope-facing surface. As a result the telescope structure and optics are predicted to radiatively cool below 25 K. The models indicate that these predictions are quite robust. Because the telescope only sees dark space and the coldest stage of the thermal shield, no telescope tube is required.

The solar and thermal shields are deployed through inflation of three tubes on their outer perimeters. One of these tubes is used to deploy the solar shield, The other two tubes deploy the thermal shield which is arranged as a v-groove radiator. In this v-groove radiator configuration, a white painted flat surface faces the spacecraft. The outer perimeter of the first stage thermal shield is connected to the outer edge of the second thermal shield at the inflation tube. The second stage shield slopes to a point which is oriented towards the telescope and nearly touches the point of the similarly shaped third stage shield, Both the second and third stage shields have specular surfaces facing space with an effective emissivity of 0.05. These surfaces comprise the v-groove radiator. The perimeter of the third stage joins the perimeter of the flat, white fourth stage at the last inflation tube. The sides of the first and second stage shields and the third and forth stage shields which see each other also have an effective emissivity of 0.05. The central 1.5 m diameter of the second, third and forth stage shields are fixed in place and made of sheet aluminum to permit conductive parasitic down the composite struts, cabling, etc. to be radiatively intercepted. It is possible with further design refinements, that the thermal shield deployment could be accomplished through deployment of the optical trusses without relying on inflation.

Rigidization of the inflated structure is required to ensure that the radiators stay deployed even if they develop a leak or suffer a micrometeor impact. A rigidization technique appropriate to the warm solar shield, which 'cures' materials by exposure to the sun's ultraviolet emissions, is currently in development. The thermal shields are rigidized in an even simpler fashion, The outer tubes of these shields incorporate a plastic band which freezes (i.e. passes through a 'glass' transition) upon cooldown, thereby substantially increasing the stiffness of the radiators, These plastic bands will also incorporate thin wire heater elements to prevent premature rigid ization during deployment, For additional robustness, the inflated perimeter tubes will be constructed with several chambers (similar to whitewater raft construction).

The size of the inflatable solar shield determines how far off the earth/sun axis the telescope can observe without reposing cold portions of the telescope to the sun. A 14 m inflatable structure has been developed in the Inflatable Antenna Experiment (IAE) INSTEP project, which flew on STS-77 in May 1996. Studies have demonstrated that an inflation pressure of approximately 50 torr is required to accomplish deployment of the antenna structure. The configuration planned for MI RORS is much smaller than, and a considerable simplification over, the IAE design.

Passive nutation damping will be employed to reduce the low resonance frequency inflatable structure settle time after spacecraft slewing to several minutes. Each of the five shields will be made of several grounded thin metalized polymer film layers (e.g. goldized Kapton). The layered structure of these shields will serve to damp higher harmonic vibrations similar to those seen during the IAE. The use of thin polymer materials is permissible in this orbit for a long duration mission due to the lack of atomic oxygen at L_2 and as the deployed shields are only providing radiant shielding and not providing any extra cooling to local heat sources (i.e. there are no tin effects to be concerned with). The tolerances required for a thermal shield, as opposed to the inflatable antenna concepts currently under development, are much relaxed. The inflatable sun/earth shield also saves considerable system mass by enabling elimination of the exterior telescope structure.

Use of an active cooler instead of a cryogen dewar significantly simplifies the instrument design, decreases the spacecraft mass, and extends the mission lifetime. A small, two-stage sorption cryocooler[6] will cool the focal plane to approximately 8 K, so there will be no dewar or expendable cryogenics. The first stage of this cooler cools optical baffles and the tip-tilt mirror to 25 K. Such a cooler has been designed which is projected to be capable of delivering 100 mW at 20 K and 10 mW at 8 K with a mass of only 25 kg and an input power of 50 watts in a flight configuration.

in addition to the low mass and power requirement of this cooler, a feature of particular importance for the MIRORS design is the ability to locate tbc warm compressor on the spacecraft 300 K heat rejection radiator, remote from the cryostat and FPA, without performance penalty. This greatly simplifies tbc mechanical and thermal design of the telescope and minimizes thermal parasitic into the passively cooled regions of the telescope. The essentially zero-vibration, zero-EMI/EMC cryostat is very small and can easily be integrated into the FPA.

Sorption coolers for applications requiring quick-cooldown to below 10 K, and periodic-operation are currently under development by BMDO to support 10 year life missions.' The Brilliant Eyes Ten Kelvin Sorption Cooler Experiment (BETSCE) developed and flew such a cooler on STS-77 in May, 1996. The experiment successfully provided flight characterization of all sorption cooler design parameters which might have shown sensitivity to microgravity effects. Full ground performance was achieved with no indications of microgravity induced changes. A continuous operation 25 K cooler is currently under development for integration with tbc UCSB CMB anisotropy Long Duration Balloon experiment.[8] Using the 25 K sorption cooler permits elimination of a 500 liter helium dewar from the balloon-borne CMB experiment. This cooler will be delivered to UCSB for instrument integration in December, 1996.

Vibration-free sorption coolers which cool as low as 4 K are to be developed at JPL under a new NASA funded development program planned to start in FY '97. Under this effort vibration-free, long-life sorption coolers will be developed to operate at approximately 25 K, 8 K and 4 K. Should the Si:As BIB detector dark current be higher than expected, a 4 K stage, using helium as the refrigerant, will be added to the baselined refrigerator.

1.6 The MIRORS spacecraft bus design

The requirements posed by the MIRORS mission are not considered stringent for today's spacecraft technologies and certainly will not be during the next decade. Based on the recent trend in downsizing spacecraft while maintaining performance capabilities, we can expect that further improvements in spacecraft technologies will continue to reduce the spacecraft bus cost, Examples of smaller, lower cost and easier-to-operate spacecraft include tbe USAF STEP series of spacecraft, GSFC's TOMS-EP and the SSTI, 'techsat' under development for NASA,

Use of an exist ing industrial spacecraft bus design is viewed as a necessity to minimize development risk and cost, given the stringent cost limitations for envisioned future astrophysics missions. The TRW Advanced Bus product line has been selected as the starting point for this study. The Advanced Bus line is actually a series of spacecraft of different sizes